

The Discovery Channel Telescope

A Wide Field Telescope in Northern Arizona

Thomas A. Sebring, Project Manager; Edward Dunham, Project Scientist;
Robert L. Millis, Director*

Lowell Observatory
1400 W. Mars Hill Road
Flagstaff, Arizona 86001

ABSTRACT

Lowell Observatory has initiated the development of a four meter class optical telescope with significant capabilities for solar system and broad spectrum astronomical research. Key to the Discovery Channel Telescope (DCT) is the ability to rapidly switch between 2 degree FOV imaging via a prime focus camera to 30 arc min FOV instrumentation at Ritchey-Chrétien (RC) focus. The telescope is to be constructed at approximately 7700 feet altitude, Southeast of Flagstaff, Arizona at a site which has exhibited 0.6 arc sec best quartile seeing. The telescope will feature active optics and alignment capability and the Prime Focus Instrument will feature a Mosaic Focal Plane array of 40 2k x 4k CCDs. The RC instrument payload will be approximately 5000 lbs, allowing either large instruments or suites of co-mounted instruments. This telescope is being developed in partnership with Discovery Communications, Inc. (DCI), who will utilize the DCT and the association with Lowell Observatory to develop educational programming about astronomy and technology. The telescope will be a substantial enhancement to the current capabilities of Lowell Observatory.

Keywords: astronomical telescope, wide-field, Lowell Observatory, Discovery Channel, DCT

1. INTRODUCTION

Lowell Observatory astronomers began discussing a telescope for the 21st century in about 1995. These discussions quickly led to a realization of the tremendous potential of a large-aperture, wide-field survey telescope. As subsequently noted in the astronomy and astrophysics decadal survey (McKee et al. 2001)¹ such an instrument would, among other things, be a powerful tool for accelerating progress in a number of high-priority research areas including the Near-Earth Asteroid problem and exploration of the newly discovered Kuiper Belt.

A purely wide-field imaging telescope would not serve the full range of scientific interests of the Lowell staff. Accordingly, a search was begun for an optical design for a 4-meter-class telescope that could deliver ultra-wide-field imaging capability, but could also be quickly switched to a significantly longer focal length configuration for spectroscopy, infrared imaging, and other applications. After an unsuccessful exploration of the Paul-Baker all-reflective design, Lowell contracted with EOS Technologies of Tucson to take an independent look at our requirements. That study (Blanco et al., 2003)², and a study independently undertaken by Harland Epps (Epps and Di Vittorio, 2003)³ demonstrated that a 2-degree-diameter field of view could be achieved at prime focus, in combination with an alternate conventional Ritchey-Chrétien or Cassegrain configuration. Prior to consummation of the partnership with DCI, Lowell discussed a telescope of this type under the project name, Next Generation Lowell Telescope (NGLT) (e.g., Millis et al., 2001).⁴

Over the past 15 months substantial progress has been realized. Establishment of a Project Office and initial staffing has enabled concept development to proceed. Contracts for conceptual design for major subsystem elements have been let, and these contractors, in concert with the DCT Project Team, have developed the configurations for all major system elements. A Concept Design Review will be conducted in mid-July of 2004, and the Project will then progress into detailed design and subsequent manufacturing and integrations phases.

* www.lowell.edu; phone 928.774.3358

2. SPECIFICATIONS

The telescope proposed here is a 4.2- meter aperture instrument featuring a 2-degree-diameter FOV prime focus camera and a second, Ritchey-Chrétien (R-C) focus capable of accepting single large or multiple small instrument payloads. The two alternate foci are accessed by a flipping mechanism, which can alternately present the Prime Focus Camera (PFC) or a secondary mirror to feed the R-C focus. Changes can be performed in 15 minutes or less, allowing a night's observing program to be tailored to the prevailing seeing conditions and to make optimum use of gray nights. The primary mirror is 100 mm thick and has active control. The optical specifications of the telescope at the two foci are listed in Table I, while Table II lists its mechanical specifications.

2.1 Table I. Major Optical Specifications of the Discovery Channel Telescope

Parameter	Prime Focus	Ritchey-Chrétien Focus
Clear Aperture	4.2 meters	4.2 meters
Effective f/ratio	2.3	6.2
Areal central obscuration	10%	10%
Linear Field of View	2 degrees	30' unvignetted
Image scale (15 μ m pixel)	0.32 "/pixel	0.12 "/pixel
Image Quality (Note 1)	0.27" FWHM	0.20" FWHM
ADC	Included	Optionally removable
UV cutoff	330 nm	300 nm (without ADC)

Note 1. Image quality includes all effects except free-atmosphere seeing.

2.2 Table II. Major Mechanical Specifications of the Discovery Channel Telescope

Parameter	Specification
Operating azimuth range	$\pm 270^\circ$
Operating zenith angle range	$0.4^\circ < Z < 85^\circ$
Maximum slew rate	3°/sec
Retargeting Time	< 6 sec for 2° move
Pointing error	< 2" rms
Pointing stability	< 0.1" jitter with 0.1"/min drift
Non-sidereal object track rates	> 5"/sec
Guiders	Non-sidereal capability
Prime/RC focus selection	Tumbling top end
Nominal RC focus payload	4000 lb

At prime focus, the telescope delivers seeing limited image quality over a 2-degree field of view. This is accomplished by use of a multi-element corrector system. The current optical design of the DCT prime focus corrector has been developed by Goodrich Aerospace of Danbury, CT. Delivered image quality at the edge of the field of the PFC is 0.27 arc sec FWHM taking into account all contributors to image degradation except free atmosphere seeing. This design has been arrived at after much optimization to minimize the number of difficult surfaces, uses fused silica for all optics with the exception of one lens and the two elements of the atmospheric dispersion compensator (ADC), and to maintain achievable alignment tolerances. The design of the PFC assembly incorporates automated filter changing and a shutter. Field de-rotation is accomplished by rotation of the focal plane camera assembly. Guiding and wavefront curvature sensing are accomplished using four peripheral detectors in the prime focus camera's (PFC's) focal plane array.

3. MAJOR SUBSYSTEMS

The major subsystems of the DCT are: Facility and Site, Dome, Telescope Mount, Telescope Optics, Prime Focus Instrument, and Electronics and Control System.

3.1 Telescope Site

About ten years ago, Millis began a search for potential observatory sites in northern Arizona. The objective was to identify possibilities at higher altitude and farther from the growing city of Flagstaff than Lowell's current site on Anderson Mesa 15 miles ESE of Flagstaff. Twelve sites were identified and studied from the standpoint of feasibility of access and perceived long-term vulnerability to light pollution. In the summer of 2001, image quality measurements were made at three of the more promising sites using the differential image motion technique (e.g., Sarazin and Roddier, 1990).⁵ Simultaneous measurements were made with identical equipment at Anderson Mesa. These measurements showed that a site near the former lumber camp of Happy Jack, 42 miles SSE of Flagstaff, gave the best image quality of the three and was consistently superior to Anderson Mesa in this regard. The attractiveness of this location was further enhanced by the presence of a paved highway and commercial power adjacent to the site. Analysis of space-based imaging by Pierantonio Cinzano (e.g., Cinzano et al., 2000)⁶ specifically commissioned for the Happy Jack site predicts a zenith sky brightness significantly below that at Anderson Mesa.

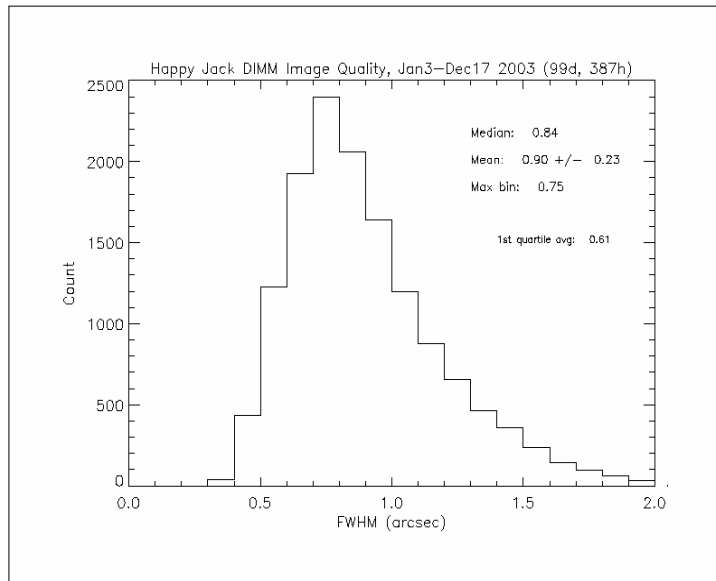


Fig. 1. Happy Jack DIMM Image Quality

In the fall of 2002, a "permanent" site testing installation was built at the 7760 ft elevation Happy Jack site and nightly measurements of image quality commenced in January 2003. The results of these ongoing measurements have been encouraging, with the median image quality consistently near 0.8 arcsec FWHM. The seeing distribution from 99 nights of observations between January 3 and December 17, 2003 is shown in Figure 1. Images in the 0.5–0.6 arcsec FWHM range occur with reasonable frequency (the average of the first quartile of the distribution is 0.61 arcsec,) and the dispersion of the seeing distribution is comparatively narrow. The validity of the theory-based conversion from our DIMM measurements to FWHM was confirmed by comparison of direct WIYN images with simultaneous DIMM measurements taken outside the WIYN dome with the Happy Jack system.

3.2 Facility Design

M3 Engineering and Technology of Tucson, Arizona has been contracted to support development of the design of the site and facility for the DCT (Figure 2). Site works include improvement of existing access roads to the summit of the cinder cone at Happy Jack, utilities, and initial leveling and grading. The facility itself will constitute about 8500 square feet of space in two levels. The observing floor is level with the dome/facility interface and the inner portion of the telescope mount yoke assembly, facilitating easy installation of RC instrumentation. This level is serviced by a hydraulic elevator assembly and incorporates a hatch through which the Primary Mirror Assembly and the Prime Focus Instrument can be lowered via the dome crane. The first floor incorporates all required spaces for electronics, control room, infrastructure such as auxiliary generators, compressors, chillers, etc., a

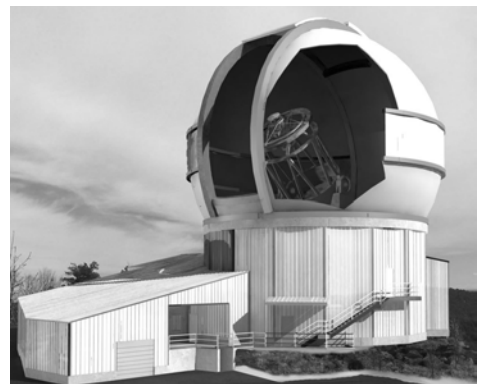


Fig. 2. Concept Rendering of DCT

high bay area suitable for assembly and disassembly of the primary mirror for coating, and a DC Magnetron primary mirror coating chamber (see Figure 3, next page). Construction is consistent with modern observatory practice; using steel framed, metal clad buildings designed to equilibrate rapidly and with interior ventilation designed to exhaust waste heat downwind of the observatory. Within the facility only the control room, instrument workspace, and computer room are actively heated and cooled, and these spaces are heavily insulated. The exterior of the building will be white to minimize solar heating. Aerial and geotechnical surveys have been performed, and foundation design for the telescope pier completed in concert with finite element and servo-control modeling.

3.3 Telescope Dome

The telescope dome will employ a steel framework and either aluminum or fiberglass composite panels. This system provides for an extremely lightweight and cost effective dome. It is anticipated that the dome will rotate via four friction drives diametrically opposed. The shutter will be a nested “over-the-top” design, and driven via chain drives. Ventilation will be provided for via 10’x10’ facets arranged about the equator of the dome, six on each side of the shutter opening. These provide mounting features for natural ventilation louvers. Alternatively, the facility will provide mounting points for downdraft ventilation fans in the enclosure cylinder wall immediately below the observing level. These will couple to short ducts which terminate in gratings in the floor of the observing level. Computational fluid dynamics modeling of the telescope facility, including the mount and dome, is currently being performed by TF Design in Capetown, SA under contract.

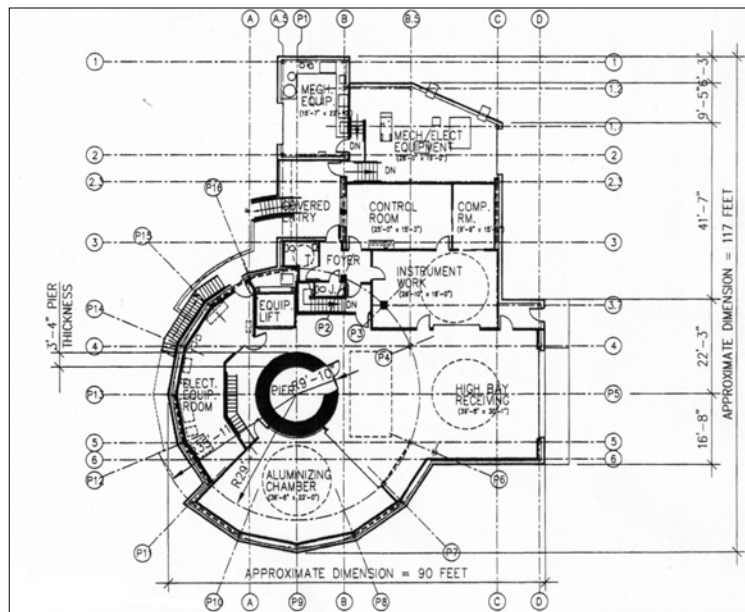


Fig. 3. Level I of DCT Facility

3.4 Telescope Mount

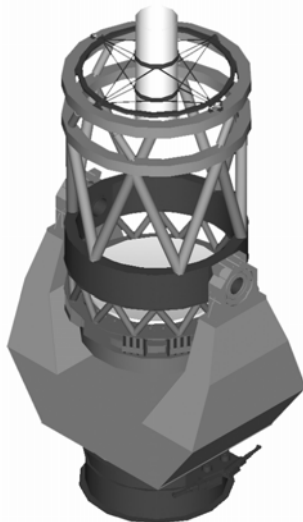


Fig. 4. DCT Telescope Mount

The telescope mount concept has been developed by Vertex RSI of Richardson, Texas in collaboration with the DCT Project Team (Figure 4). The mount is based on the designs developed for the SOAR Telescope⁷ and incorporates a rolling element bearing for azimuth motion with recirculating oil lubrication and driven by four counter-torqued motors through helical gears. Elevation motion also utilizes rolling element bearings, though with direct drive torque motors acting on each side of the elevation ring. All motors are liquid cooled to minimize heat put into the observing environment. A unique aspect of the DCT Mount is the ability to flip the spider assembly to alternately present the Prime Focus Instrument or, the secondary mirror to feed the RC instrument/s. This flip is accomplished manually, by an operator with the telescope pointed at horizon and with access to the flip mechanism provided by a platform on the observing level of the facility. The flip is to be accomplished in less than 15 minutes including any necessary re-alignment of the telescope. Alignment of the telescope in both operational modes is accomplished by two mechanisms. Coarse alignment is achieved using a large and unique hexapod arrangement which separates two upper rings. This arrangement provides for 6 degree-of-freedom motion of the spider assembly relative to the primary mirror and RC instrument package. Resolution of this system is 10 microns in focus, insufficient accuracy to meet image quality requirements.

Fine alignment for tip/tilt and focus is provided by the Primary Mirror Assembly using the fine figure actuators. Decenter requirements are sufficiently met by the hexapod system alone. Results obtained with the SOAR Telescope mount indicate that tracking accuracy is sufficient for unguided tracking for short, 30-second exposures anticipated for the routine survey work performed by the Prime Focus Instrument. For longer exposures guiding and low order wavefront sensing are anticipated.

3.5 Telescope Optics

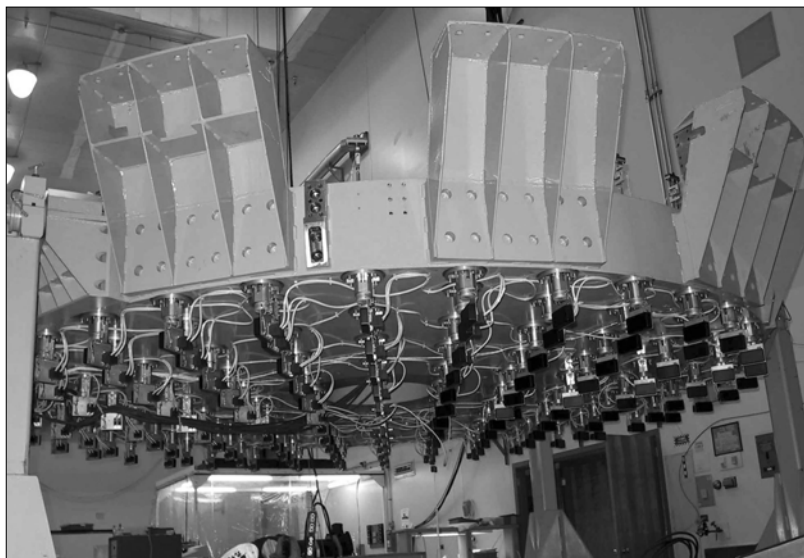


Fig. 5. Acuator Svstem for SOAR Primarv Mirror

It is anticipated that an active primary mirror system similar to that employed by the SOAR Telescope (Figure 5) will be incorporated. However, at this writing the procurement for this system has not been completed, and options for other types of primary mirror systems remain open. The SOAR type, provided by Goodrich Optics and Space Systems of Danbury, CT is an electro-mechanically actuated active optic, with loop closed on in-line force transducers at low bandwidth to obviate wind driven errors. Actuators are axially stiff and do not permit deformation of the optic due to wind pressure. The primary mirror cell is bolted into a Ritchey-Chrétien Instrument Adapter which mounts to the rear surface of the mount elevation ring.

The entire assembly is installed and removed from the telescope mount with the mount pointing to the zenith, and the primary mirror assembly is lowered to the high bay area in the facility by the dome crane. The primary mirror will be actively figure controlled, and length adjustment of the fine figure actuators will also be used to adjust focus and tip/tilt alignment of the primary to the Prime Focus Instrument and RC position. The secondary mirror will be a lightweighted optic, either via machining or via Corning Glass' proprietary frit bonding process. This enables better balance of the Prime Focus Instrument package about the flip axis and aids in overall elevation stage balance. A contract has been signed between Lowell Observatory and Corning Glass⁸ for a 4.3 meter diameter primary mirror and a 1.3 meter diameter blank for the secondary mirror.

3.6 Prime Focus Instrument

Goodrich Optics and Space Systems have been contracted to perform the overall optical design of the DCT, including the conceptual design of the Prime Focus Instrument (PFI) (Figure 6)⁹. The optical corrector for the PFI incorporates nine optical elements (see Figure 7, next page) including the two components of the atmospheric dispersion compensator and a spectral filter. Iterations on the design have resulted in acceptable residual aberrations, though the task of obtaining good images to the edge of the 2 degree FOV required many design iterations. All elements are fused silica with exception of the ADC elements which use other optical glasses. The largest lens is approximately 1.2 meters in diameter. The design task has included development of an all Invar metering structure, lens cells, and mechanisms including shutter, filter changer, and ADC transport. Finite element modeling supported optimization has brought gravity and thermally driven performance of this system within acceptable parameters.

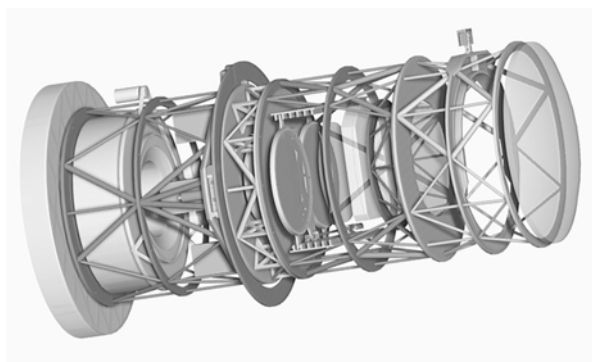


Fig. 6. DCT Prime Focus Instrument

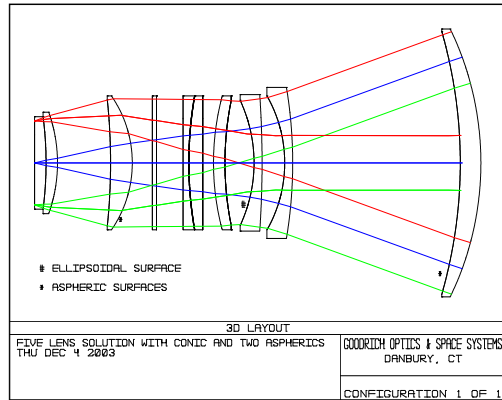


Fig. 7. Wide-Field Corrector

The system incorporates a field derotation system which rotates the camera dewar only and a powered cable wrap is provided to enable the precision servo positioning required to obtain required angular precision of the camera rotation stage. e2v Corporation of Chelmsford, Essex, England have been contracted to develop the mosaic focal plane array assembly. The mounting plate is anticipated to be of Invar and e2v is responsible for design of wiring and mounting to achieve the required 10 micron PV flatness required for the entire array. The dewar will be engineered and built by the instrument development group at Lowell Observatory under the guidance of the Project Scientist, E.W. Dunham. Cooling is anticipated to be via 4 Cryo-tigers mounted to the rear surface of the dewar with the cryogen pumps to be mounted off-telescope for good control of waste heat.

3.7 RC Focus

The RC focus offers an unvignetted 30-arc min field of view, and good IR performance as all components of the prime focus camera and corrector system reside within the obscuration of the secondary mirror. An instrument rotator mounting will carry either single instruments up to about 5,000 lbs or an instrument adapter incorporating guiding and wavefront sensing capabilities that can mount up to three smaller ready-to-go instruments and provide switching between them. The instrument adapter may make use of either a fast tip/tilt mirror or can be upgraded to adaptive optics.

3.8 Wavefront Sensing and Guiding

Operation of the DCT at either instrument location will incorporate the use of high resolution wavefront sensing for image quality optimization and low order wavefront sensing during astronomical observation. Current plans call for use of the entire focal plane array of the PFI for curvature-sensing-based high resolution wavefront measurement. This will support development of lookup tables providing correct primary mirror actuator force suites and alignment positions for wide ranges of elevation and temperature. During short exposures, as in survey mode, the mount will track accurately and no guiding will be required. For longer exposures, the peripheral CCD's in the mosaic array will be read out periodically to provide guiding and low order wavefront / focus updates. The Astronomy Technology Centre of Edinburgh, Scotland has been contracted to provide information regarding their development of curvature based wavefront sensing algorithms and designs for the VISTA Telescope Project. While plans for wavefront sensing and guiding at the RC focus are immature at this point, incorporation of either Shack Hartmann or curvature sensing based methods of calibration and operational wavefront sensing measurement into either instruments or multiple instrument adapters is straightforward and has been done previously on other telescopes.

3.9 Control System

Conceptual design of the control system for DCT incorporates a PCI platform based architecture communicating via fast Ethernet¹⁰. Machines will run either Linux or Windows based operating systems. National Instruments LabVIEW software will be stipulated for all subsystems and the top level Telescope Control System. This architecture provides for cost effective platforms, choice of a wide variety of hardware, a software environment which has over 15 years of legacy, and substantial corporate support. The system is also flexible and provides for simple incorporation of existing algorithms in almost any language and for interface of different hardware standards.

4. PROGRAMMATIC ISSUES

The DCT was given a substantial boost with the formal establishment of the relationship with Discovery Communications in 2003. In addition, over the year starting from 01 March 2003, a dedicated office building for the Project Team was constructed at Lowell Observatory. The initial five members of the Project Team have been hired, and the development contracts identified above were let. A Concept Design Review and formal cost review have been scheduled for July of 2004, and pending successful conclusion of this review, the DCT Project anticipates moving ahead into detailed design, manufacturing, and integration activities. Use of the proposed telescope site is dependent on

award by the United States Forest Service of a Special Use Permit, as the site is located within the Coconino National Forest. Environmental assessments are currently underway pursuant to the applicable statutes of the United States Government. If all goes according to plan, groundbreaking could occur as early as November of 2004, with First Light currently anticipated in mid 2008.

5. ASTRONOMICAL SCIENCE

Research currently planned for the DCT runs the gamut from solar system studies to cosmological research. Space limitations do not allow us to discuss in detail each program. Instead, we discuss below a few examples including three imaging surveys that are likely to consume significant telescope time during the initial years of operation.

5.1 Kuiper Belt Objects

On a clear night of good seeing, the Deep Ecliptic Survey finds between 15 and 20 Kuiper Belt Objects (KBOs). With its much wider field of view and shorter readout time, the Discovery Channel Telescope and prime focus camera can be expected to yield approximately five times as many objects per unit time. Consequently, mapping of the extent of the belt in ecliptic latitude can be efficiently extended and a much more comprehensive sample of the KBO populations obtained. Currently lost objects will be quickly rediscovered in this comprehensive search and owing to the greatly extended observational baselines, accurate orbits for these objects will be immediately obtained. In addition to simply discovering KBOs, the DCT will enable a variety of follow-up physical studies including measurements of color, determination of rotational characteristics, and estimation of shape and/or albedo variation. Similarly, orbits will be determined for wide KBO binaries found in survey mode and the masses of these systems calculated.

5.2 Photometric Search for Extra-Solar Planets

Many ground-based transit search programs are now underway (e.g., Horne, 2003, Charbonneau, 2003)^{11,12} including the PSST program at Lowell (Dunham, et al. 2004).¹³ The figure of merit for such searches is essentially the $A\Omega$ product of the observing system. The DCT prime focus camera is spectacular in this regard. Its short read time is also important because the large aperture of the DCT will require short exposures to be used in order to obtain photometry of stars sufficiently bright for high resolution radial velocity follow-up observations.

5.3 Extending the Search for Near-Earth Objects

Current NEO search programs are unable to reliably detect NEOs smaller than about 1 km in diameter. The Discovery Channel Telescope, however, will have the capability to do much better. Its large FOV, fast-readout camera, faint limiting magnitude (about $V = 23$ for 20-s integrations on moving objects), and large rate of sky areal coverage (100–200 deg²/hr), make it a powerful and well-adapted instrument for discovering NEOs at an unprecedented rate. Indeed, modeling suggests that DCT will be able to detect 20–40 NEAs/hr, together with hundreds, perhaps thousands of main-belt asteroids. Thus DCT can surpass the current worldwide rate of NEO detection by an order of magnitude or more, and, over the course of a few years, could sample most NEOs larger than 500 m in diameter, thus very greatly increasing our knowledge of the impact hazard. Moreover, because of its ability to quickly switch to the R-C instruments, the DCT can obtain valuable data bearing on the physical properties of selected NEOs during the relatively short interval after discovery that they are sufficiently bright.

5.4 Selected Stellar and Galactic Research Programs

The 2-degree FOV prime focus imager also provides a unique opportunity for stellar and extragalactic studies. These studies will be further enhanced by the complement of RC focus instruments that will be available at the time of commissioning, plus others to be brought on-line later. One example of the sort of stellar project for which this telescope will be well-suited is the study of Galactic clusters and OB associations. Much of what we know of Galactic structure, and of stellar evolution, derives from early studies of such regions (i.e., Morgan, Sharpless, and Osterbrock, 1952; Morgan, Whitford, and Code, 1953; Johnson and Sandage, 1953).^{14,15,16} Modern studies combining CCD photometry and spectroscopy have begun answering some of the fundamental questions of star formation, such as the universality of the initial mass function and the history of star formation within a cluster. (A good recent example is the study of the η and Chi Persei double-cluster by Slesnick, Hillenbrand, and Massey 2002).¹⁷ The size of a typical OB association at a distance of 2 kpc is still 1–2 degrees, making such modern studies difficult without a very wide FOV imager. The use of IR imaging further allows one to “cut through the muck” of interstellar extinction, revealing sites of star formation that would otherwise go undetected in the optical. One such recent example is the study of the region

around the well-known optical OB association Cygnus OB2 (see Massey and Thompson 1991 and references therein)¹⁸ by Knodlseder (2000)¹⁹ using 2MASS data; he suggested that it might be an example of a “super star cluster” containing over 100 O stars. This suggestion has been partially confirmed by Hanson (2003)²⁰, who suggests that nearby regions of the Milky Way may contain many more such super star clusters.

6. CONCLUSIONS

The Discovery Channel Telescope represents a significant step forward in wide field astronomical imaging capability. The following table contains a comparison of the DCT with other existing or planned telescopes having significant survey capability. In this regard, the relevant parameter is $A\Omega$ where A is the collecting area of the telescope in square meters and Ω is the area of the sky in square degrees covered in a single exposure. Note that in this parameter, the DCT exceeds all existing telescopes with only the planned Pan-STARRS and LSST projects having greater values.

Telescope	Diameter	Collecting Area	Solid Angle	$A\Omega$
UH 2.2-m/PFCam	2.2	0.8	0.25	0.2
Palomar/Quest	1.2	1.1	16.60	18.3
CFHT/Megacam	3.6	10.0	1.00	10.0
MMT/one-degree camera	6.5	33.2	1.00	33.2
Subaru/Suprimecam	8.0	50.2	0.25	12.6
Discovery Channel Telescope	4.2	13.9	3.10	43.1
Pan-STARRS	3.6	10.0	7.00	70.0
LSST	8.3	54.0	7.00	378.0

It is anticipated that due to the largely conventional nature of the telescope, focal plane array, CCDs, and the straightforward application of existing telescope technology that the development of the DCT will be rapid, is low risk, relatively low cost, and will place Lowell Observatory squarely in the forefront of several aspects of astronomical research.

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